# COOLSIDE DESULFURIZATION DEMONSTRATION AT OHIO EDISON EDGEWATER POWER STATION

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#### **ABSTRACT**

The Coolside Process is a duct sorbent injection process developed for retrofit SO2 control in a coal-fired boiler. The attractive features of the process for retrofit use include low capital cost, low space requirements, and short construction time. The demonstration project was conducted on the 104 MWe Unit 4-Boiler 13 at the Ohio Edison Edgewater Power Plant, Lorain, Ohio, under a partial sponsorship of the U.S. Department of Energy (DOE) Clean Coal Technology Program. The full-scale test results confirmed the SO2 removal capability of the process, as previously observed in pilot plant tests, and the soundness of the basic process design concept for operation in a utility environment. Additionally, the demonstration provided information on process equipment design improvements required for commercial operation.

This paper focuses on the process  $SO_2$  removal performance observed in the demonstration. Potential research areas for improving the process performance based on the full-scale results are discussed.

#### INTRODUCTION

In 1986, Babcock & Wilcox, Consolidation Coal Company (Consol), the State of Ohio Coal Development Office, and Ohio Edison Company, under the sponsorship of the DOE Clean Coal Technology Program, agreed to demonstrate the Coolside and LIMB processes at the Ohio Edison Edgewater Station. The demonstration of the Coolside process was conducted from late July 1989 to mid-February 1990, using compliance (1.4 wt % S) and non-compliance (3 wt % S) bituminous coals from Ohio (Table 1). The objectives of the full-scale program were to verify the process performance in regard to short-term operability and SO2 removal, to determine factors which could affect long-term operations, and to develop a data base to establish process economics and design parameters. The demonstration program included sorbent once-through and sorbent recycle operations. Key process variable effects were evaluated in short-term (6-8 hr) parametric tests and longer-term (1-14 day) process operability tests. Two different hydrated limes (Table 2) were tested. Prior to the demonstration, pilot-scale tests were conducted to select the hydrated limes to be tested and to develop process performance data applicable to the Edgewater site-specific conditions. The pilot data were used for demonstration program planning and data interpretation. This paper discusses full-scale Coolside desulfurization results at the Edgewater Station Unit 4-Boiler 13 in Lorain, Ohio. The discussion of the results is limited to the observations from once-through process tests. Recycle process tests (in which a portion of the collected ash is reinjected into the flue gas to increase overall sorbent utilization) were performed but the data are not included here because data analysis was not completed at the time this paper was written. Coolside pilot-scale process performance (1-5) and full-scale design and operation (6) were described elsewhere.

#### PROCESS DESCRIPTION

Coolside desulfurization technology involves dry injection of hydrated lime into the flue gas downstream of the air preheater and flue gas humidification by water sprays (Figure 1). SO2 is captured by reaction with the entrained sorbent particles in the humidifier and by the dense sorbent bed collected in the particulate removal system. The humidification water serves a dual purpose. First, it activates the sorbent to enhance SO2 removal and, second, it conditions the flue gas and particulate matter to maintain efficient electrostatic precipitator (ESP) performance. Spent sorbent is removed from the gas along with fly ash in the existing particulate collector (ESP or baghouse). The sorbent activity can be significantly enhanced by dissolving sodium hydroxide (NaOH) or sodium carbonate (Na2CO3) in the humidification water (3-5). Sorbent recycling can be used to improve the sorbent utilization if the particulate collector can handle the resulting increased solids loading. For reasons of convenience and cost, NaOH was used as the additive in the Edgewater demonstration.

#### EDGEWATER HUMIDIFIER DESCRIPTION

The Edgewater equipment and process operations were described in detail elsewhere  $(\underline{6})$ . Because humidification is crucial to the Coolside process, a short description of the Edgewater humidifier follows. The Edgewater humidifier was designed to avoid forming wet deposits on the walls. Figure 2 shows a drawing of the humidifier and the ductwork connecting it to the existing plant equipment. The humidification chamber was erected on the roof of the boiler house. Its dimensions were 14-feet 7-inches x 14-feet 7-inches, and 56-feet long. A 10 x 10 array of Babcock & Wilcox Company Mark 12 atomization nozzles at the humidifier entrance provided the fine water sprays for the flue gas humidification. The hydrated lime injector ports were located at the same vertical plane as the atomizer array. The humidifier was designed for a flue gas flow rate of one million pounds per hour, which gives about a 2.5 second humidifier residence time. However, air in-leakage through the air preheater resulted in a higher-than-design flue gas rate (1.3 million pounds per hour at full boiler load of 104 MWe). This increased flow necessitated that, at full load, a portion of the flue gas by-pass the humidification chamber. The original plant ductwork between the air preheater and the ESP was used for the flue gas by-pass. The data reported here, however, are only from tests at lower load in which all of the flue gas passed through the humidification chamber.

Thermocouples to measure flue gas temperature were located at the humidifier inlet and exit and at the ESP inlet. Humidification was controlled by varying the water flow rate to maintain a preset humidifier outlet temperature based on the thermocouples located at the humidifier exit. The flue gas was continuously monitored at the humidifier inlet and the ESP exit (stack) for SO2 and O2.

## PROCESS DESULFURIZATION PERFORMANCE

# Desulfurization Performance Overview

The Edgewater program demonstrated that the Coolside process can routinely achieve up to 70% SO2 removal at the design conditions of 2.0 Ca/S and 0.19 Na/Ca molar ratios and 20°F approach to adiabatic saturation temperature using a commercial hydrated lime (Lime A). Use of an alternate hydrated lime (Lime B) gave somewhat lower SO2 removals, as did a 25°F approach; these effects will be discussed in detail later in this paper. A range of SO2 removals between 30 and 70% was achieved by controlling the Ca/S and Na/Ca molar ratios and the approach to adiabatic saturation temperature. The SO2 removals measured in these tests were confirmed by ash analysis results, as discussed in a later section. The SO2

removal results were consistent with projections based on Consol 0.1 MWe pilot plant and 1 MWe field test data.

Sorbent once-through utilizations of up to 35% were observed. This indicates that there is room for significant process improvement if the sorbent utilization can be increased through process optimization, including sorbent recycle. When calculating sorbent utilization, NaOH is included as a co-sorbent since it also captures SO2 as Na2SO3 or Na2SO3.

The process was operated round-the-clock. During most operations, the ESP was able to handle the increased solids loading resulting from the sorbent injection and kept the flue gas opacity level below 5%. The acceptable performance of the ESP was largely the result of flue gas humidification. Without humidification, the ESP would not have been able to handle the increased solids loading and particle resistivity caused by sorbent injection (7).

#### Variable Effects

<u>Ca/S Ratio</u>. The data obtained at Edgewater show an increase in SO<sub>2</sub> removal with Ca/S ratio for the two hydrated limes tested (Figure 3). The SO<sub>2</sub> removal using hydrated lime B at 23 to  $26^{\circ}$ F approach to adiabatic saturation are shown as squares, while the removals using hydrated lime A are shown as crosses for tests at 23 to  $26^{\circ}$ F approach, and as circles for 19 to  $22^{\circ}$ F approach to adiabatic saturation. No tests were performed using hydrated lime B at 19 to  $22^{\circ}$ F approach because, by this point in the test program, the humidification performance had deteriorated to the point where operation at  $20^{\circ}$ F set point caused the formation of large droplets, leading to wet deposits formation at the humidifier outlet. Using hydrated lime A, SO<sub>2</sub> removals were 40, 50 and 70% at average Ca/S molar ratios of 1.1, 1.4 and 2.0, respectively. The process conditions were 19 to  $22^{\circ}$ F approach to adiabatic saturation; 0.17 to 0.24 Na/Ca molar ratio; and coal sulfur content between 2.0 to 2.8 wt %. The SO<sub>2</sub> removals with hydrated lime B showed a similar trend, although they were lower than those with hydrated lime A. Although the observed SO<sub>2</sub> removals at similar Ca/S ratios had some variation, Figure 3 clearly shows the trend of higher SO<sub>2</sub> removals at higher Ca/S ratios. The Ca/S ratio is an important process variable to maintain SO<sub>2</sub> removal at a desired level. As was shown in pilot plant (4.5) and other field tests (1), SO<sub>2</sub> removal increases in a predictable manner with increasing Ca/S ratio.

The  $SO_2$  removals were calculated from the  $SO_2$  concentrations measured at the humidifier inlet and ESP outlet using continuous gas analyzers which were corrected to dry, excess-air-free conditions. Corrections for air in-leakage were made using continuous oxygen analyzer data collected at both locations. The moisture content was calculated based on measured wet bulb and dry bulb temperatures. The Ca/S ratio was calculated based on the measured  $SO_2$  concentration in the flue gas entering the humidifier, the measured flue gas flow rate into the humidifier, and the measured hydrated lime feed rate to the humidifier.

Approach to Adiabatic Saturation Temperature. At a constant Ca/S and Na/Ca molar ratio, SO2 removal was higher when the process was operated at closer approach to adiabatic saturation (or wet bulb) temperature. The effect of only a few degrees variation in the approach to adiabatic saturation can be observed by comparing the circles (19 to 22°F approach) with the crosses (23 to 26°F approach) in Figure 3. This comparison shows that, at equivalent Ca/S ratios, the observed SO2 removals were 6 to 10 percentage points (absolute) higher in the tests at 19 to 22°F approach than in tests at 23 to 26°F approach over the range of Ca/S ratios in the figure. The effect of larger variation in the approach to adiabatic saturation is given by Figure 4, which shows SO2 removal as a function of the approach to the

adiabatic saturation temperature using hydrated lime A at Ca/S molar ratios of 1.4 and 2.0; the Na/Ca molar ratio was 0.17 to 0.24. Although some variation occurred in the observed  $SO_2$  removals at similar approach temperatures, the data demonstrate that the  $SO_2$  removal is higher at closer approaches to adiabatic saturation temperature.

Variations in the approach to adiabatic saturation were not intended as part of the demonstration test program. The variations shown in Figure 4 occurred for two reasons. First, the approach varied because of variations in the humidifier exit temperature from the control point and some fluctuations in the flue gas wet bulb temperature. Second, the set point for the approach was increased from 20 to 25°F during the tests with lime A. This change was necessary because of the change in the humidifier performance.

Na/Ca Ratio. At constant Ca/S and approach to adiabatic saturation, the SO2 removal was higher when NaOH was added to the humidification water. Using hydrated lime A at a 2.0 Ca/S molar ratio and 23 to 26°F approach to adiabatic saturation temperature, SO2 removals were 60 to 65% in tests with additive (0.19 Na/Ca molar ratio) but only 35 to 45% in tests without additive. Since NaOH additive significantly enhances SO2 removal, and demonstration of maximum SO2 removal was the project goal, tests without NaOH were limited. Thus, no data were obtained at 1.0 Ca/S without additive, nor were data obtained at higher approaches without additive. The effect of sodium additive on SO2 removal performance was established in previous pilot plant studies (3-5). The full-scale results were in good agreement with pilot data on the additive effect.

Effect of Different Hydrated Limes. Hydrated lime A gave higher SD2 removals than hydrated lime B at similar process conditions. This is shown for the conditions 0.17 to 0.24 Na/Ca molar ratio and 23 to 26°F approach to adiabatic saturation temperature by comparing the crosses (Lime A) with the squares (Lime B) in Figure 3. This comparison shows that, at equivalent Ca/S ratios, the observed SO2 removals were 5 to 10 percentage points (absolute) higher when using hydrated lime A than when using hydrated lime B over the range of Ca/S ratios in the figure. These results are consistent with pilot plant results that showed higher SO2 removals when using hydrated lime A than when using hydrated lime B (5). Both are high calcium (>88% Ca(OH)2 by wt) hydrated limes. Differences in physical properties, such as surface area, may have contributed to the performance differences. The BET surface areas were 22 to 24 m²/g for hydrated lime A and 15 to 18 m²/g for hydrated lime B. Previously reported work showed a correlation between sorbent surface area and SO2 removal performance (5).

# Comparison with Pilot Plant and Field Tests

In preparation for the demonstration tests at Edgewater, Consol conducted pilot plant tests on a 0.1 MWe scale and a 1 MWe scale. Figure 5 compares the SO2 removals at Edgewater with those observed in the 0.1 MWe pilot plant (4.5) and 1 MWe field tests (1) for the conditions of 2.0 Ca/S and 0.19 Na/Ca molar ratios. The data shown from the Edgewater and the 1 MWe field tests were from tests at 20°F approach; the data from the pilot plant were from tests at 25°F approach to adiabatic saturation. The sorbent was hydrated lime A for the Edgewater and pilot plant data and a third lime, hydrated lime C for the field test data. In pilot plant tests, the SO2 removals using hydrated lime C were about 5 to 10% (relative) lower than those using hydrated lime A (5). The 70% SO2 removal achieved at Edgewater compares well with the 75% SO2 removal observed in the 1 MWe field tests. In both of these tests, an ESP was used for particulate control. These removals were lower than the 85% SO2 removal observed in pilot plant tests. However, a baghouse was used for particulate collection in the pilot plant. Because a

baghouse provides more effective gas-sorbent contact than an ESP, the SO $_2$  removals were expected to be somewhat lower at Edgewater than in the pilot plant tests. These results, along with the consistency in the variable effects of the pilot and Edgewater tests, as discussed above, indicate that the 0.1 MWe pilot plant unit is a reliable device for simulating process performance, for evaluating improved sorbents, or for conducting site-specific simulations.

In addition to the difference in the particulate removal device, differences in other design/operating factors of the Edgewater Coolside system from the pilot plant may have affected the comparison of  $SO_2$  removal performances at Edgewater and at the pilot plant. These factors include water droplet size distribution, water droplet and hydrated lime distributions in the gas, and flue gas velocity and flow distribution. However, the effects of these differences on  $SO_2$  removal were not quantifiable from the current Edgewater data.

#### Edgewater Data Reliability

Table 3 compares the sorbent utilizations based on the sulfur, Ca, and Na contents of the ESP hopper samples with the sorbent utilizations calculated from the process run data for tests using hydrated lime A. Samples also were taken during tests using hydrated lime B, but the analyses were not completed when this paper was written. The average difference between the two methods was 0.87% (absolute). This agreement is good, considering the relatively small size of the ESP samples (50-100 lbs) taken from a single ESP hopper, of which 100 grams was submitted for analysis, compared with the large amount of solids (2 to 10 tons/hr) collected by the ESP which had a total of twelve hoppers. A standard statistical F Test (8) on the data in Table 3 shows that the differences between the results of the two methods of determining sorbent utilization were not significant. Using the twelve process runs and the two methods of determining utilization in Table 3 as the sources of variance, the F-number for the method variance/residual variance was 0.87 for 1/11 degrees of freedom. This indicates that the probability that the two methods gave truly different results was not significant.

## <u>Directions for Desulfurization Performance Improvement</u>

Since the observed sorbent utilization is low (25-35%), there is a significant potential for improving process economics by optimizing the process design for maximum  $SO_2$  removal efficiency. Process optimization is possible in several areas. Improved dispersion of the sorbent in the flue gas may improve the  $SO_2$  removal. Sorbent recycle, involving reinjection of spent sorbent recovered from the ESP, offers a straightforward means of enhancing the sorbent utilization as long as the ESP and the waste handling system installed in the plant can handle the increased solids loading. Sorbent recycle tests were performed during the Edgewater demonstration, but the data analysis was not completed at the time this paper was written

In the longer term, optimization of the sorbent (hydrated lime) properties for  $SO_2$  capture is expected to lead to an improved sorbent. Pilot plant tests have shown a positive correlation of hydrated lime surface area with sorbent utilization. Lime hydration methods that produce high surface area hydrates are being studied at Consol R&D (9) and elsewhere (10). Additive incorporation during lime hydration also may provide more reactive sorbents (2,11).

## CONCLUSIONS

The Edgewater Coolside testing demonstrated  $SO_2$  removals up to 70% in an electric utility boiler burning an eastern United States high-sulfur coal.

- Sorbent utilizations at these SO2 removals were typically 30 to 35%. spent sorbent analyses confirmed the sorbent utilizations based on the continuous flue gas analyzers.
- The full-scale SO2 removals were similar to pilot-scale SO2 removals. This indicates that appropriate pilot-scale tests are a good predictor of fullscale performance for this technology.
- As observed in the pilot-scale tests, the process  $SO_2$  removal depends on the primary process variables: Ca/S and Na/Ca molar ratios and the approach to adiabatic saturation.
- Differences in the hydrated lime affect the SO2 removal level.

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TABLE 1
TYPICAL COAL ANALYSES\*

		Proximate Analysis		1	Ultimate Analysis					
		_	Volatile	Fixed						
<u>Coal</u>	Btu/lb	<u>Moisture</u>	Matter	Carbon	Ash	_ <u>c</u> _	<u>H</u> _	<u>N</u>	<u> </u>	(by diff.)
Compliance	13204	4.18	34.75	54.74	10.51	74.48	4.92	1.39	1.42	7.29
Non-Compliance	12695	4.12	37.98	48.91	13.11	70.72	4.88	1.25	3.02	7.02

\*All analyses except moisture are wt % dry basis.

TABLE 2
TYPICAL HYDRATED LIME ANALYSES

Hydrated	BET Surface	TGA Data, dry wt %			
<u>Lime</u>	<u>Area. m²/g</u>	Ca(OH)2	CaCO3		
A	23.2	93.0	2.5		
В	16.7	88.0	2.5		

TABLE 3
COMPARISON OF ESP ASH ANALYSES AND PROCESS RUN DATA

% Sorbent Utilization Based on SO<sub>2</sub> Removal, Ca/S and Na/Ca\* % SO2 Ach Ca/S (mol) Na/Ca (mol) <u>Removal</u> <u>Analysis</u>\*\* Difference 0.00 41.1 26.3 30.0 -3.7 1.89 0.19 58.6 28.3 5.4 -0.7 46.9 44.7 52.7 53.7 1.21 33.9 34.6 31.8 32.5 0.7 1.45 0.18 34.2 33.8 1.40 32.0 26.7 33.0 2.05 0.23 45.7 24.7 32.9 0.11 1.96 1.03 0.00 0.00 Average 0.87

<sup>2</sup> SO<sub>2</sub> Remova( Ca/S + 0.5 (Na/S)

<sup>\*\*</sup>  $\frac{Total\ Sulfur/32}{\text{CaO/56} + \text{Na}_2\text{O/62}}$ , CaO and Na<sub>2</sub>O corrected for calcium and sodium in coal ash

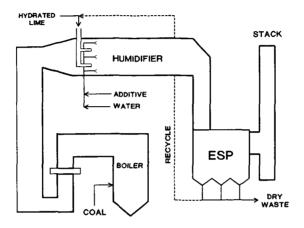


Figure 1. Coolside Process Schematic..

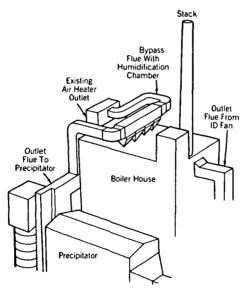


Figure 2. Edgewater Coolside Demonstration Process Equipment Layout.

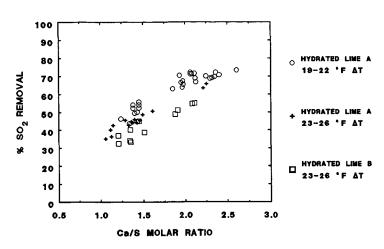


Figure 3. SO<sub>2</sub> Removal vs Ca/S Ratio. These data were obtained at a nominal Na/Ca mol ratio of 0.19.  $\Delta T$  is the approach to adiabatic saturation at the humidifier outlet.

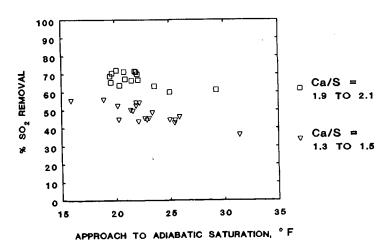


Figure 4. SO<sub>2</sub> Removal vs Approach to Adiabatic Saturation for Operation With Hydrated Lime A. The Na/Ca molar ratio was 0.17-0.24 in these tests.

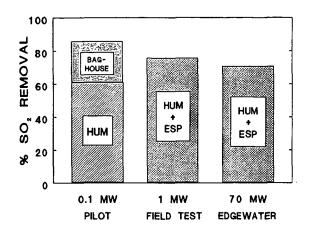


Figure 5. Comparison of Pilot, Field and Demonstration Test SO<sub>2</sub> Removal Performance: Ca/S - 2 mol ratio, Na/Ca = 0.19 mol ratio, 20-25°F approach to adibatic saturation.